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Technological Fundamentals for Efficiency Control of Hydroabrasive Cutting

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Abstract

On the basis of the criterion function analysis of the technological system and analysis of its active elements of a two-level hierarchal model of hydroabrasive cutting functioning, a procedure for the assessment of the efficiency control of technological system states has been developed, and in accordance with this procedure an efficiency criterion has been further proposed to show the impact of various technological factors upon the machining quality and productivity. A procedure for the assessment of efficiency control of the technological system states for the productivity increase has been developed; it involves assurance of a maximum value of a criterion function of the echnological system work allowing one to choose the most efficient technological parameters increasing the machining productivity at minimum energy consumption

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Keywords: hydroabrasive cutting; technological system;control; criterion function; measure of efficiency

1. Introduction

The industrial experience of hydro-cutting equipment operation shows particularly visibly the influence of all structural elements in the technological system control upon the efficiency of cutting operations performed: on one and the same technological base a working result can be directly opposite (from the worst to the best quality of working). At the same time there is not yet created a single methodological approach to the control of a technological system in hydroabrasive cutting as a multi-level system with a hierarchical structure.

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Nomenclature

$p(\mathrm{v})$	is high-speed head, in Eq. (1)
$c(v)$	is costs for material cutting, in Eq. (1)
$H(v)$	is specific wear, in Eq. (2)
$\sigma(v)$	is power consumption, in Eq. (2)
$H_1(v)$	is the effectiveness of the conversion of fluid flow potential energy p by a nozzle into kinetic one, in Eq. (5)
$\sigma_1(v)$	is the expenses of the technological system for the creation of the essential fluid high-speed flow in nozzle supply channels, in Eq. (5)
n	is the capacity of a fluid flow, W
q	is the quantity of power in fluid flow essential for the destruction of a mass unit of material, J
ρ	is the liquid density, кg/м^3
f	is the jet section area, mm^2
ε	the jet compression ratio, in Eq. (10)
p	is the surplus static pressure, Pa
m	is the mass flow, кg/s
Q	is the volumetric liquid discharge, m^3/s
v	is the average flow rate, mm/s
P_z	is cutting force, H
V_p	is rate of a board motion of destruction, m/s

Most authors of researches obtained more or less substantiated recommendations for the technological parameter choice of control for concrete conditions [1-3]. On the one hand, such an approach allows researching a problem of optimum condition choice for working as a part of the general problem of a technological system control, on the other hand, it limits the results obtained by the framework of a concrete meaningful interpretation. Furthermore, in the overwhelming majority of models a multiple submission of the technological system elements is not taken into account.

To increase working effectiveness most of researchers confine themselves to a basic two-level organization system consisting of the control center on the upper level and active elements on the lower level.

One of the explanations of researchers' attention concentration upon two-level hierarchical systems consists in the possibility of the structure decomposition into a set of elementary "blocks".

In this case the problem solution of the analysis consists in the introduction of the efficiency criterion which is the measure of an achievement degree in a working goal..

For instance, the measure of technological system efficiency may be capacity or hydroabrasive cutting quality.

Numerous investigations of the capacity in various material hydroabrasive cuttings show that with the jet pressure increase the maximum force of a stream effect upon material grows on the dependence close to a linear one [4-9]. Physical and stress-strain properties of material machined which are expressed with the totality of a number of strength characteristics have a great influence upon cutting efficiency [10].

To identify qualitative and quantitative effects between a center of control and active elements we will carry out a decomposition and analyze one-element two-level system.

2. Evaluation of the effectiveness of the process of waterjet cutting

As a jet effect force upon material is in the direct proportion to the velocity squared of a jet outflow, for the active element (AE) of the technological system is chosen an effective value of the outflow velocity v. At the same time AE obtains the essential high-speed head $p(v)$ from the technological system and incur costs $c(v)$ for material cutting.

In the same way, the criterion function of AE "supersonic stream" becomes,

$$f(v) = p(v) - c(v) \tag{1}$$

Informally within the bounds of this model (1) the technological system of hydroabrasive cutting must at least compensate energy loss of AE, for instance, power supplied must be equal to inputs for cutting. At the same time, in the first place, if the velocity of jet outflow v is such, that cutting force is larger than the created force of flow affecting material, then a through cutting is impossible at the preset efficiency and, secondly, creating an flow pressure equal to the inputs for cutting, we obtain a possibility to find out the best solution realizable for a technological system.

At the prescribed flow pressure p the technological system of hydroabrasive cutting obtains a required capacity due to the AE activity expressed through the material specific wear $H(v)$, defined by the jet outflow velocity v, at the same time it should be taken into account that to achieve an essential jet outflow velocity the technological system incurs certain power consumption $\sigma(v)$.

Wherefrom the criterion function of the technological system of hydroabrasive cutting is,

$$\mathrm{F}(v) = H(v) - \sigma(v) \tag{2}$$

Within the bounds of such an interpretation under the effectiveness of a technological system work is implied the maximum value of a criterion function,

$$K_0(C) = \max_{v \in P(C)} \left[H(v) - c(v) \right] \tag{3}$$

Where $P(C)$ is the state set of a “supersonic fluid jet”: active element,

$$P(C) = \left\{ v \in A \middle| c(v) - \min c(v) \le C \right\} \tag{4}$$

3. Management structure of technological system waterjet cutting

The fulfilled analysis of functional structures in hydroabrasive cutting shows that as a control center of the element group realizing a basic function of the technological system is a nozzle which interacts with all elements of the system and forms a cutting tool – a hydroabrasive jet.

The pattern of changes in hydro-dynamic parameters of the jet on the length (the length of an initial part, core diameter, cutout, velocity of abrasive or liquid and others) is in direct dependence on parameters of a nozzle [11].

To the key features of a nozzle which could be used in hydroabrasive cutting control belong [12]:

- design parameters (method for liquid and abrasive mixing, the embodiment of nozzle component parts and others);
- geometrics (nozzle diameter, the length of a focusing tube, inner geometrics of jet forming openings and others);
- dynamics (mass shown and others);
- hydrodynamics (discharge of liquid and abrasive, loss factor, flow pressure factor and others);
- nozzle spatial orientation.

In the hierarchical structure of the technological system control in hydroabrasive cutting the intermediate center – C_1 – “jet forming nozzle” the criterion function of which is equal to,

$$\mathrm{F}_1(v) = H_1(v) + \sigma_1(v) - \sigma(v) \tag{5}$$

At that the criterion function of the technological system center becomes,

$$\mathrm{F}(v) = H(v) - \sigma_1(v) \tag{6}$$

At the same time the criterion function of an active element “supersonic stream” is invariable.

As a result the technological system for hydroabrasive cutting may be presented as a three-level one-element system (Fig. 1).

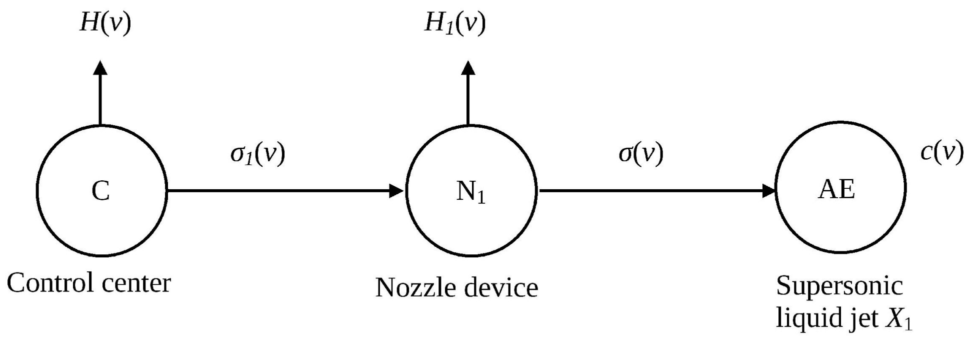

Fig. 1. Structure of the three-level one-element technological system for hydroabrasive cutting.

Set of actions realizable in the three-level structure of technological system control is defined through the following dependence,

$$R(p) = \left\{ v \in A \middle| c(v) - \min c(v) - H_1(v) \le c \right\} \tag{7}$$

4. Example of calculating the efficiency of management of waterjet cutting

We consider an example showing the effectiveness of the introduction additional hierarchy levels into the structure of the technological system control for hydroabrasive cutting.

Cutting-out productivity will be defined by velocity of nozzle device feeding relative to material at its complete cutting through. Changing pressure of operating fluid, diameter and a nozzle inner profile, that is, changing the value of energy supplied on a unit of material surface and being aware of the design value for material to be moved away and charge essential for its destruction it is possible in each case to determine time for machining various sorts of material, and hence, productivity.

The depth of jet penetration into material at a short time interval is larger considerably of the horizontal displacement of a nozzle head determined by a feed rate,, that is why a contact area of the interaction a jet and material could be conditionally considered motionless in the horizontal plane actually for all cases of jet cutting. The horizontal velocity of a nozzle feed is approximated by the sequence of stages the sizes of which correspond to a nozzle diameter in the course of time required for through cutting out of material [13]. In such a way, material is cut out by means of a gradual travel of the destruction front into the depth.

In the steady mode the rate of a board motion of destruction is defined as follows,

$$V_p = \frac{n}{q} \tag{8}$$

Taking into account, that the rate flow is a value in direct proportion to the force F and jet velocity v, we obtain an expression for the definition of the velocity of jet feed with regard to material,

$$S = \frac{Fv}{qV_p} \tag{9}$$

Material cutting force is defined through the following dependence,

$$P_z = (0,5 + \varepsilon)\rho f v^2 \tag{10}$$

Then from (3) follows, that the action set realizable by a technological system of hydroabrasive cutting:

$$P(P_z) = \left[0; \sqrt{\frac{P_z}{(0,5+\varepsilon)\rho f}} \right] \tag{11}$$

Wherefrom (4) the effectiveness of two-level control in the technological system of hydroabrasive cutting,

$$K_0(P_z) = \max \left\{ \frac{F}{qV_p} \sqrt{\frac{P_z}{(0,5+\varepsilon)\rho f}} - P_z, \frac{\left(F / qV_p\right)^2}{(0,5+\varepsilon)\rho f} \right\} \tag{12}$$

Now introduce an intermediate center -“jet forming nozzle”.

We define a power conversion ratio of an environment stream with the aid of a nozzle, as a ratio of specific kinetic energy of a jet at the outlet from a nozzle to surplus specific potential energy of flowing medium at the inlet,

$$q = \frac{mv^2}{2pQ} \tag{13}$$

Then from (13) taking into account (10) we obtain,

$$R(p) = \left[0, \frac{1}{(0,5+\varepsilon)\rho f} \left(\frac{m}{2pQ} + \sqrt{\left(\frac{mv^2}{2pQ}\right)^2 + (0,5+\varepsilon)\rho f p} \right) \right] \tag{14}$$

It is clear that minimum energy consumption in the technological system is achieved at the agreement of energy consumption in the subsystem $C(P_z)$ and in the technological system $C(p)$, that is, provided that,

$$C(P_z) - C(p) = H_1(v) \tag{15}$$

From (15) follows, that,

$$C(p) = C(P_z) - \frac{m}{2pQ}\left(\frac{F}{qV_p} + \frac{m}{2pQ} \right) / \left((0,5+\varepsilon)\rho f\right) \tag{16}$$

Obtain dependence for the definition of three-level system in the control of technological system in hydroabrasive cutting,

$$K_1(P_z) = \max\left\{ \left(\frac{F}{qV_p} + \frac{m}{2pQ}\right)\sqrt{\frac{P_z}{(0,5+\varepsilon)\rho f}} - P_z, \frac{\left(\frac{F}{qV_p} + \frac{m}{2pQ}\right)^2}{(0,5+\varepsilon)\rho f} \right\} \tag{17}$$

Compare the effectiveness of the technological system control in hydroabrasive cutting with two-level and three-level structure having introduced in formulae (12) and (14) averaged values of the magnitudes f = 0,00758; ρ = 1000 кg/м^3, ε = 1, P_z = 10 H, Q = 0,00005 m^3/s, p = 4×10^5 Pa, m = 0,5 кg/s, V_p = 60 m/s, q = 0,045, F = 100 H.

Wherefrom:

$$K_0(P_z) = (55,55;437,81) \tag{18}$$

$$K_1(P_z) = (55,58;438,03) \tag{19}$$

The larger effectiveness factor of the technological system work is, the more effective is a hydroabrasive cutting procedure.

Comparing $K_0(P_z)$ and $K_1(P_z)$ we obtain that at any value of P_z $K_1(P_z) \geq K_0(P_z)$, that points to the effectiveness increase in the technological system control in hydroabrasive cutting at the introduction of an additional control center-"nozzle device".

5. Coordination of technological parameters of waterjet cutting

To ensure high productivity we strived for expenditure decrease for material cutting through the reduction of material removal at a time unit. But at ensuring quality of a cut surface it is necessary that the limitation should be introduced for jet volume affecting the unit of a surface machined at a time unit [14, 15].

In this case the order of technological system functioning in abrasive cutting is as follows: starting from the required quality of the cut surface $H(\Delta_i)$, the value of material removal $c(Q)$ is defined. After that the AEs of the technological system choose the actions maximizing their criterion functions depending on $c(Q)$. In its turn the value $c(Q)$ is composed of the consumption of operating fluid $\sigma(Q)$ and the rate of nozzle feed relative to the material S.

The assessment of the working effectiveness of the technological system $K(C)$ should be carried out on the dependence (3) for every discrete area.

There is developed a methodology for the assessment of the effectiveness control in technological system states for productivity increase which consists in ensuring a maximum value of the criterion function of the technological system operation allowing the choice of the most effective technological parameters increasing machining productivity at minimum power consumption by the technological system,

$$K_1(P_z) = \max\left\{ \left(\frac{F}{qV_p} + \frac{m}{2pQ}\right)\sqrt{\frac{P_z}{(0,5+\varepsilon)\rho f}} - P_z, \frac{\left(\frac{F}{qV_p} + \frac{m}{2pQ}\right)^2}{(0,5+\varepsilon)\rho f} \right\} \tag{20}$$

Hence, this implies a significant conclusion essential for the comprehension of the productivity increase problem in hydroabrasive cutting. At equal energy consumption on the side of a technological system it is possible to use a number of technological techniques allowing the increase of a process productivity [17 - 20]. They are reduced to the expenditure decrease for material cutting $c(v)$ by means of operating fluid expenditure control through a nozzle device, outflow pressure increase, the increase of nozzle feed rate and so on (Fig. 2).

There is developed a procedure for the assessment of the effectiveness in technological system state control to achieve a prescribed quality and accuracy in machining allowing the destination for subsystems the agreed technological parameters ensuring required roughness, accuracy of a form and the location of a cut surface.

In accordance with the compensation principle it is necessary to solve the following problem of agreed control,

$$x_{\Delta} = \arg\max\left\{H(\Delta) - c(V)\right\} \quad (21)$$

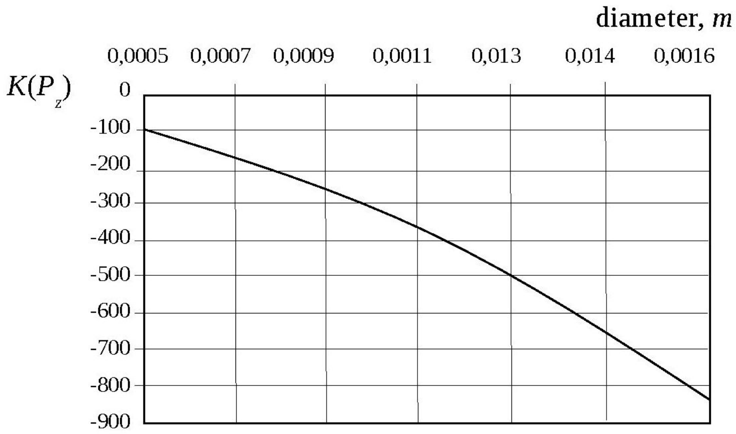

Fig. 2. Influence of a nozzle diameter change upon working effectiveness of the technological system for ensuring the productivity of hydroabrasive cutting: outflow pressure p = 400 MPa; rate of nozzle feed S = 0,5 m/min.

As the required value of the accuracy parameter $H(\Delta)$ must be constant then, using the expression (6), it should be possible to determine a required intensity of destruction v_0 and concentrate special attention on the solution of optimum technological parameter choice for a nozzle feed rate, outflow pressure, abrasive grain expenditure.

In such a way, the value of material removal to achieve a prescribed accuracy is limited with the value v_0, then, solving the problem of condition optimization to achieve a required roughness of a surface, we obtain that the efficient factor of the technological system is,

$$K(V_0) = \left\{ (c_p p^{c1} S^{c2} a^{c3}) \left(\frac{V_0}{a^3} \frac{\pi L^3 tg^2 \beta}{3} \right) - V_0 \right\} \quad (22)$$

In the physical sense it means that the higher the rate of fluid flow is and the less nozzle feed is, then the larger amount of grain crests has an influence upon the geometrics of surface roughness, that finally results in the decrease of the height of these surface imperfections (Fig.3),

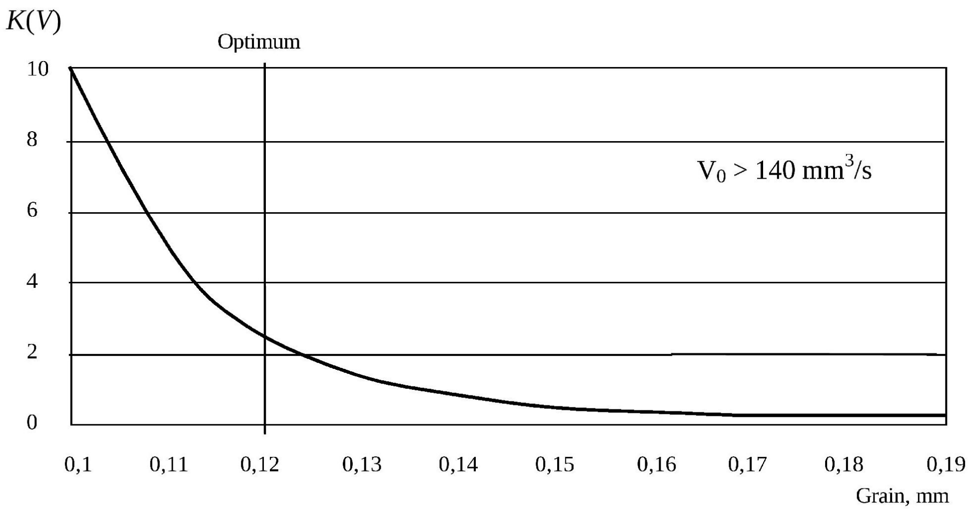

Fig. 3. Dependence of the working effectiveness of the technological system in hydroabrasive cutting on the agreed assurance of accuracy and roughness of a cut surface upon abraive grains: flow pressure p = 400 MPa; feed S = 0,5 m/min; nozzle diameter d= 0.50 mm; optimum volumetric loss V_0 = 140 mm^3/s; material thickness h = 50 mm.

6. Conclusion

On a basis of the criterion function analysis of the technological system and its active elements of a two-level hierarchal model of hydroabrasive cutting functioning there is developed a realization concept and a procedure for the assessment of the control effectiveness of technological system states in accordance with which there is developed a criterion of effectiveness showing the impact of various technological factors upon machining quality and productivity.

There is developed a procedure for the assessment of control effectiveness of technological system states for the productivity increase consisting in assurance of a maximum value of a criterion function of technological system work allowing the choice of the most effective technological parameters increasing machining productivity at minimum energy consumption on the side of the technological system.

The procedure for the assessment of effectiveness in control of technological system states to achieve prescribed accuracy and quality in machining allowing the assignment for subsystems the agreed technological parameters ensuring required roughness, form accuracy and the location of a cut surface is developed.

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